Searches beyond the Standard Model at HERA

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At HERA, new physics processes beyond the SM are probed in $e^{\pm}$-proton collisions at a center of mass energy of $300-318$ GeV. Recent results on searches obtained by the H1 and ZEUS experiments are presented with an emphasis on data taken in e^-p collisions in the years 1998/99 and in e^+p collisions in the years 1999 and 2000.

Introduction

At the HERA collider, electrons (positrons) and protons are collided at a center of mass energy of about $\sqrt{s} = 318\,\mathrm{GeV}$ ($300\,\mathrm{GeV}$ before 1998), directly probing new physics in eq interactions at the highest energies. Since 1994, integrated luminosities of about $\mathcal{L} = 115\,\mathrm{pb}^{-1}$ in e^+p and $\mathcal{L} = 15\,\mathrm{pb}^{-1}$ in e^-p scattering have been collected by the two experiments H1 and ZEUS. The most recent data collected in e^+p scattering in the most successful year 2000, corresponding to about $\mathcal{L} = 60\,\mathrm{pb}^{-1}$, increased significantly the sensitivity to new processes. First results are presented here.

Indirect Searches

Measuring the deep inelastic scattering process (DIS) $e^{\pm}p \rightarrow e^{\pm}X$ at the highest momentum transfers (Q^2) gives indirect access to new particles such as heavy bosons, leptoquarks and composite particles or to quantum gravity effects above the center of mass energy of HERA. No deviation from the SM expectation was found in the most recent data [1,2]. Therefore limits on new physics processes have been set using the formalism of four-fermion (point-like) contact interactions. Limits are derived by fixing the SM couplings and by fitting additional new vector-type couplings $L_V = \sum_{a,b=L,R} \eta^q_{ab} \, (\bar{e}_a \gamma^{\mu} e_a) \, (\bar{q}_b \gamma_{\mu} q_b)$ to the data, where $\eta^q_{ab} = \epsilon \frac{g^2}{(\Lambda^q_{ab})^2}$ are model-dependent coefficients of the new process, g is the coupling constant, Λ^q_{ab} is the effective

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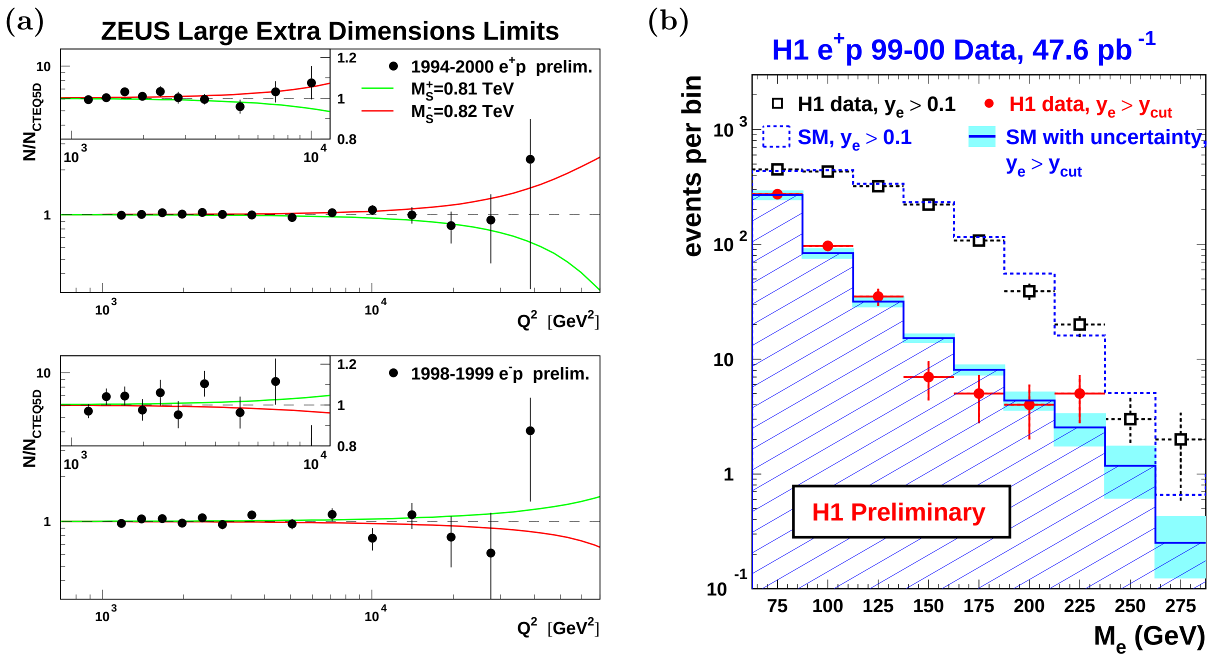

Figure 1: (a) Ratio of the observed number of events over the expectation in Neutral Current DIS as a function of Q^2 as measured in e^+p and e^-p scattering by ZEUS. The fitted curves show the 95% CL exclusion limits on large extra dimensions for constructive and destructive interference with the SM process. (b) Distribution of the $e-$jet invariant mass as reconstructed from the scattered positron for all events (*open squares*) and after applying an optimised angular cut (*full circles*) to enhance the discrimination between leptoquarks and SM processes. The data were taken by H1 in the most recent 1999-2000 e^+p run.

mass scale and $\epsilon = \pm 1$ is a parameter determining the interference with the SM. Fits were performed simultaneously to the e^+p and e^-p data and 95% confidence limits (CL) were derived. Using almost full data statistics, H1 excludes compositeness scales [3] up to about 9 TeV assuming $g^2 = 4\pi$.

Similarly, limits can be set on models with Large Extra Dimensions (LED) [4], see fig. 1 (a), in which SM particles are bound to a (3+1)-dim. space while gravitons live in a world with $\delta \geq 2$ extra compactified dimensions. This model solves the hierarchy problem by bringing down gravitation to the TeV scale, i.e. the electroweak scale. Gravitons are expected to appear in the (3+1)-dim. world as towers of Kaluza-Klein modes and gravitation is actually a strong force at short distances below the size of the compactified extra dimensions. Gravitation has been tested directly only down to the milli-meter scale, so it is attractive to test the LED model at HERA and other collider facilities where compactification at the TeV scale can be tested.

95% CL limits have been derived by fitting the SM Lagrangian with an additional term $\propto \epsilon/M_s^4$, which accounts for the graviton exchange with M_s being an effective compactification mass scale. 95% CL limits were set by the H1 experiment [3]: $M_s^+ > 0.6\,\text{TeV}$ and $M_s^- > 0.9\,\text{TeV}$ and by the ZEUS experiment: $M_s^{\pm} > 0.8\,\text{TeV}$.

Direct Searches

The existence of leptoquarks, excited fermions and scalar quarks, which are predicted by Grand Unification (GUT), compositeness and supersymmetry (SUSY) models, can be probed directly by looking for eq-resonances or characteristic decays of new particles. All these particles would be dominantly singly produced at HERA and the cross-section depends therefore quadratically on the coupling of the new state to SM particles.

The excess observed in neutral current DIS e^+p data 1994-1997 at positron-quark invariant masses at about 200 GeV by H1 [5] was not confirmed by the recent data taken in 1999-2000

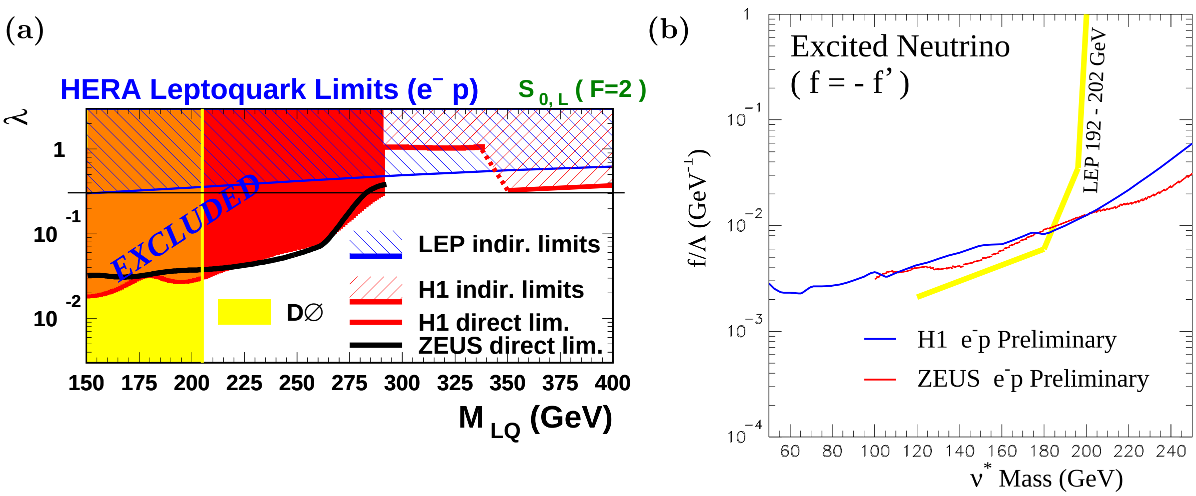

Figure 2: (a) Exclusion region of λ as a function of the $S_{0,L}$ leptoquark mass. For $M_{LQ} < \sqrt{s}$ the limits from direct searches performed by H1 and by ZEUS are shown. For $M_{LQ} > \sqrt{s}$ the limit derived by the indirect search from H1 is shown. For comparison, the limits obtained by LEP and D0 are also shown. (b) Exclusion limits on f/Λ for the excited neutrino search as a function of the ν^* mass. The limits are shown for the coupling assumption f $= -$f$'$ as measured by H1 and ZEUS. For comparison, the limit obtained by DELPHI [15] is also shown.

for which the invariant mass distribution is shown in fig. 1(b) [6]. A similar excess observed by ZEUS [7] for masses above 220 GeV was also not confirmed by the most recent data [2].

Different types of leptoquarks (LQ) can be probed at HERA and results are presented here in the framework of the BRW model [8]. The seven $F = 0$ scalar and vector LQs, which couple simultaneously to one fermion and one antifermion, are better probed in e^+p collisions due to the large valence quark densities of the proton. Similarly, the seven $|F| = 2$ scalar and vector LQs, which couple to two fermions or two antifermions, are better probed in e^-p collisions.

Searches for all types of LQs have been performed and no deviation from the SM was found. Results for a $S_{0,L}$ LQ with fermion number $F = 2$ are shown in fig. 2(a) using the BRW model where the $S_{0,L}$ LQ decays equally into eq and νq. 95% CL limits on the Yukawa coupling λ have been derived from the direct searches performed by H1 [9] and ZEUS [10] as a function of the LQ mass. For masses above the collider energy, the result taken from the indirect contact interaction search obtained by H1 [11] is shown. For comparison, the indirect limit obtained by LEP and the direct limit from D0, which is independent of the Yukawa coupling, are also shown.

Searches for excited states of fermions like e^*, ν^* and q^* have been made by H1 [12] and ZEUS [13] in all final state topologies resulting from the decay of a excited fermion into an electroweak boson. No significant deviation from the SM expectation was found in any of the decay channels. In general, both the single f^* production and the branching ratios of f^* depend on the gauge group weights f$'$, f and f$_s$ which describe the relative couplings of an excited fermion to the gauge groups $U(1)_Y$, $SU(2)_L$ and $SU(3)_c$ [14]. Therefore all possible decay channels were combined for certain assumptions on the relative gauge group weights and limits were set on the ratio of the gauge group weight over compositeness scale, f/Λ. As an example, fig. 2(b) shows the HERA limits on ν^* production assuming f $= -$f$'$ for which photonic decays are allowed. The limits extend beyond those obtained at LEP to ν^* masses larger than 200 GeV. Similar limits were set on the production of e^* and q^*.

Scalar quarks as predicted by SUSY can be produced directly via $ep \rightarrow \tilde{q}X$ at HERA if $\not{R}_p$ is explicitly broken by the term $\lambda'_{ijk} L_i Q_j \bar{D}_k$ [16]. Scalar quarks can decay either directly into lepton and quark or via gauge couplings into quark and gaugino followed by a $\not{R}_p$ SUSY decay. Since in these particular decay modes Majorana particles may be involved, the final state is expected to contain electrons (or positrons) explicitly violating lepton number conservation. Therefore

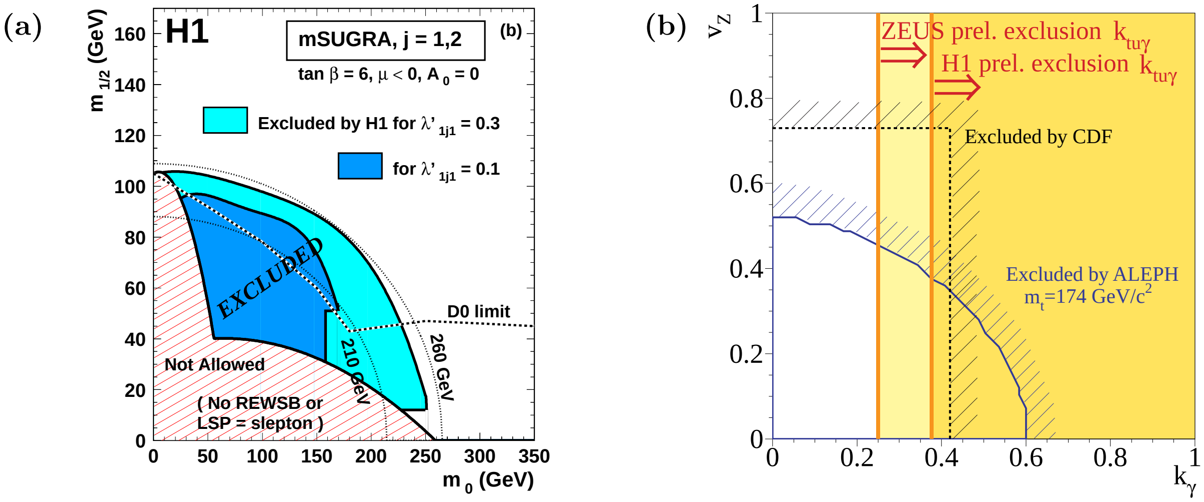

Figure 3: (a) Domain of the plane $(m_0, m_{1/2})$ excluded for $\tan\beta = 6$ for a $\not{R}_p$ coupling $\lambda'_{1j1} = 0.1, 0.3$ $(j = 1, 2)$. The region below the dashed curve is excluded by the D0 experiment and does not depend on the Yukawa coupling. Also shown are two isolines for the mass of the $\tilde{u}^j_L$ as dotted curve. (b) Excluded regions in the plane v_Z versus κ_γ. H1 and ZEUS set limits on the anomalous coupling $\kappa_{tu\gamma}$. For comparison, the exclusion limits obtained by ALEPH and by CDF are shown.

these decay modes are almost background free. Searches have been performed by H1 [17] and ZEUS [18] which essentially cover 100% of all decay topologies. No significant deviation from the SM expectation was found. By making SUSY parameter scans limits on λ were set in an unconstrained MSSM model by both experiments where the scalar quark mass is treated as a free parameter. Scalar quark masses up to about 260 GeV have been excluded for all generations for $\lambda'_{\text{Yukawa}} = \sqrt{4\pi\alpha_{em}} \approx 0.3$. The limits were found to be almost independent of the MSSM parameters. Similar limits were set by H1 for the mSUGRA model. As an example, fig. 3 (a) shows the H1 result in the plane $(m_0, m_{1/2})$ for a first or second generation squark.

Isolated Lepton Events

Excitement was caused by the observation of an anomalously large number of isolated high-energy lepton events with missing transverse momentum by the H1 experiment [19]. The ZEUS experiment has presented a similar analysis of isolated lepton events including all events taken from 1994-2000. The result, after applying two different cuts on the transverse momentum of the hadronic final state (p_t^X), is shown in the following table in comparison to the SM expectation, which is mainly W production.

Preliminary Results	p_t^X cut	**Electrons** Obs./expected (W)	**Muons** Obs./expected (W)
H1 1994-2000	$p_t^X > 25$ GeV	$3/1.05 \pm 0.27$ (0.83)	$6/1.21 \pm 0.32$ (1.01)
e$^+$p (82 pb^{-1})	$p_t^X > 40$ GeV	$2/0.33 \pm 0.10$ (0.31)	$4/0.46 \pm 0.13$ (0.43)
ZEUS 1994-2000	$p_t^X > 25$ GeV	$1/1.14 \pm 0.06$ (1.10)	$1/1.29 \pm 0.16$ (0.95)
e$^\pm$p (130 pb^{-1})	$p_t^X > 40$ GeV	$0/0.46 \pm 0.03$ (0.46)	$0/0.50 \pm 0.08$ (0.41)

The number of events observed by H1 obviously deviates from the SM expectation and from the ZEUS measurement whilst the MC expectation after all cuts is in good agreement between both experiments. Higher statistics (HERA2) and smaller uncertainties on the estimation of the dominant W-boson background (NLO calculation) will be needed to resolve this puzzle.

After applying further cuts on the isolated lepton events the final state signature of a high

p_t^X jet and an isolated lepton has been used to test anomalous single production of top quarks $ep \to etX$ where t decays semi-leptonically. This process probes new physics at the $ut\gamma$ vertex. Limits on the anomalous magnetic coupling $\kappa_{ut\gamma}$ obtained by H1 and ZEUS [20] are shown in fig. 3 (b) where H1 included also the hadronic decay channel $t \to b\,\mathrm{jet\,jet}$. For comparison, also limits on κ_γ and v_Z (the anomalous vector coupling between Z, top and light quark) obtained by ALEPH and CDF are shown.

Summary

Searches for compositeness, excited fermions, quantum gravity effects, leptoquarks, and $\not{R}_p$ SUSY have been performed and no significant deviation from the SM was found at HERA1 by either of the experiments H1 and ZEUS. As presented, data taken at HERA1 have a big exclusion power for physics beyond the SM. Currently the HERA accelerator is being upgraded to provide ten times higher integrated luminosities and, in addition, longitudinally polarized $e^\pm$ beams. Exploring the large discovery potential of HERA2 with the recently upgraded H1 and ZEUS detectors will certainly be interesting and help to resolve the puzzle of the isolated lepton events. An exciting time for searches to come...

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